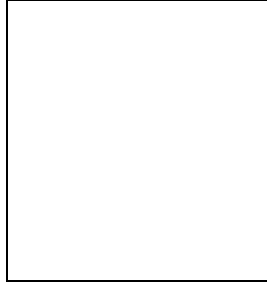# ULTRA-HIGH ENERGY COSMIC RAYS AND DIFFUSE PHOTON SPECTRUM

P.G. TINYAKOV

*Institute for Nuclear Research,*
*60th October Anniversary prospect 7a, 117312 Moscow, Russia*

It is argued that if extragalactic magnetic fields are smaller than $2 \times 10^{-12}$ G the flux of ultra-high energy photons of (a few)$\times 10^{-1}$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ predicted in top-down models of UHE CR implies similar flux of diffuse photons in the energy range $10^{15} - 10^{17}$ eV, which is close to the existing experimental limit.

In this talk I discuss possible relation between the flux of Ultra-High Energy (UHE) photons and the diffuse photon flux in the energy range $10^{15} - 10^{17}$ eV, which occurs under certain conditions. Namely, if extragalactic magnetic fields are sufficiently small, a large fraction of energy carried by UHE photons is transformed into $10^{15} - 10^{17}$ eV photons, so that the energy fluxes of these two components become comparable. In this way a flux of $10^{15} - 10^{17}$ eV photons can be produced which is close to the existing experimental limit.

There are three main issues to be considered: propagation of the diffuse photons, propagation of UHE photons and synchrotron radiation in the inhomogeneous Galactic magnetic filed. Let us start with the diffuse photons.

The detection of the diffuse photon flux at energies around $4 \times 10^{14}$ eV has been reported by the Tian-Shan experiment [1] which gives the value $I_\gamma(E > 4.0 \times 10^{14}\,\text{eV}) = (3.4 \pm 1.2) \times 10^{-13}$ cm$^{-2}$s$^{-1}$. More recently, the bounds have been obtained at higher energies, the most stringent ones coming from EAS-TOP and CASA-MIA. These bounds are $2.5 \times 10^{-14}$ cm$^{-2}$s$^{-1}$ at $E \sim 10^{15}$ eV [2,3] and $5.4 \times 10^{-17}$ cm$^{-2}$s$^{-1}$ at $E \sim 2.2 \times 10^{16}$ eV [3].

The sources of diffuse photons include, in particular, electromagnetic cascades and secondary pions produced during the propagation of UHE CR through intergalactic space. Regardless of the particular model the spectrum of diffuse photons is expected to have a dip at energies $10^{15} - 10^{17}$ eV due to the $e^+e^-$–pair production on cosmic microwave background [4]. The cross section of the latter reaction reaches maximum of 0.2 barn near the threshold at $3 \times 10^{14}$ eV, so

that the attenuation length of photons in this region is as small as $\sim 20$ kpc. Thus, a large flux of photons in this energy range can only be produced by nearby sources, while the absence of the dip in the spectrum would require that these sources contribute a large fraction of the total flux of diffuse photons.

One of the mechanisms which allows to produce the high energy photons in our Galaxy makes use of the synchrotron radiation of the electron component of UHE CR in the Galactic magnetic field. The UHE electrons are generically produced in the halo models of UHE CR in the course of the fragmentation process and rapidly convert their energy into synchrotron radiation[5]. Another possibility which is not related to halo models but requires large fraction of photons in UHE CR and small extragalactic magnetic fields is that UHE electrons are generated during the cascade propagation of UHE photons[6]. In this paper we concentrate on this latter possibility.

To make the discussion quantitative consider the equations which describe the electromagnetic cascade in the absence of magnetic field (the details can be found , e.g., in ref.[7]). The main reactions driving the cascade are $e^+e^-$ pair production (PP) on the radio background, $\gamma\gamma_b \to e^+e^-$, double pair production (DPP), $\gamma\gamma_b \to e^+e^-e^+e^-$, and inverse Compton scattering (ICS), $e\gamma_b \to e\gamma$. If one neglects secondary particles and energy losses then PP and DPP lead to the conversion of photons to electrons with the rates $a_{PP}$ and $a_{DPP}$, respectively, while ICS converts electrons back to photons with the rate $b$. At the distance $R$ from the source the electron to photon ratio is given by

$$\frac{n_e}{n_\gamma} = \frac{ae^{R(a+b)} - C}{be^{R(a+b)} + C} ,$$
(1)

where $a \equiv a_{PP} + a_{DPP}$ and $C$ is an integration constant whose value is irrelevant far from the source. Since the observed fluxes are saturated by large distances, the ratio of electron to photon flux is

$$\frac{F_e}{F_\gamma} \sim \frac{a}{b}.$$
(2)

The latter ratio depends on energy. Numerically,

$$\frac{F_e}{F_\gamma} \sim 2 \quad \text{at} \quad E = 10^{22} \text{ eV},$$
(3)

$$\frac{F_e}{F_\gamma} \sim 10 \quad \text{at} \quad E = 10^{23} \text{ eV}.$$
(4)

Thus, the flux of UHE photons implies at least as large flux of UHE electrons. The extragalactic magnetic field can substantially reduce this ratio. Estimates show that extragalactic magnetic fields smaller than $2 \times 10^{-12}$ G do not spoil our argument.

Finally, consider the synchrotron radiation of UHE electrons in the Galactic magnetic field. An ultra-relativistic particle of energy $E$ moving in the magnetic field $B$ emits radiation at the characteristic frequency

$$\omega_c = \frac{3\sqrt{\alpha}B}{2m_e^3}E^2 = 6.7 \times 10^{14} \left(\frac{E}{10^{20} \text{ eV}}\right)^2 \left(\frac{B}{10^{-6} \text{ G}}\right) \text{ eV}.$$
(5)

As a result of this process, the particle looses energy at the rate

$$\frac{dE}{dx} = -\frac{2\alpha^2 B^2}{3m^4}E^2.$$
(6)

In the magnetic field of the form

$$B(x) = B_0 \exp(x/x_0),$$
(7)

where $x_0 \sim 4$ kpc [8], the dominant radiation frequency changes with particle energy according to the following equation,

$$\omega_c(E) = \frac{9E_0^{3/2}}{2m_e\sqrt{3\alpha x_0}}f(E/E_0),$$

where $f(y) = y^{3/2}(1-y)^{1/2}$ and $E_0$ is the initial energy of the electron. Thus, most part of the electron energy is emitted at frequencies close to

$$\omega_{max} = \omega_c(3E_0/4) = \frac{27E_0^{3/2}}{32m_e\sqrt{\alpha x_0}} = 0.8 \times 10^{15} \left(\frac{E_0}{10^{22} \text{ eV}}\right)^{3/2} \left(\frac{x_0}{4 \text{ kpc}}\right)^{-1/2} \text{ eV}. \qquad (8)$$

According to eqs.(5) and (8), at $E = 10^{22}$ eV the electron looses most part of its energy in the region where the magnetic field is $B \sim 10^{-10}$ G.

Finally, let us estimate the flux of synchrotron photons assuming the flux of UHE photons typical for top-down scenarios, (a few) $\times 10^{-1}$ eV cm$^{-2}$s$^{-1}$sr$^{-1}$ at energies $\sim 10^{22} - 10^{23}$ eV. Eq.(3) implies that outside the Galactic magnetic field there is at least as large flux of UHE electrons which transfer their energy to high energy photons in the Galactic magnetic field. Since the synchrotron spectrum has $\delta\omega \sim \omega$, the energy conservation implies that the flux of synchrotron photons is approximately the same as the flux of UHE electrons, which is larger by the factor $F_e/F_\gamma$ than the flux of UHE photons. One therefore obtains the diffuse photon flux in the range $10^{15} - 10^{17}$ eV of the order of $\sim 1$ eV cm$^{-2}$s$^{-1}$sr$^{-1}$.

To summarise, we have shown that the expected dip in the photon spectrum at energies $10^{15} - 10^{17}$ eV may be filled by the synchrotron radiation of UHE CR in the Galactic magnetic field. The mechanism we propose requires small extragalactic magnetic fields and large fraction of photons in UHE CR at energies $10^{22} - 10^{23}$ eV. The last requirement is satisfied in the top-down models of UHE CR. The flux of $10^{15} - 10^{17}$ eV photons produced by our mechanism in these models is close to the present experimental limit. Thus, it is important to improve the sensitivity of the experiments in the energy range $10^{15} - 10^{17}$ eV. The detection of the diffuse photon flux at the level of $\sim 10^{-1}$ eV cm$^{-2}$s$^{-1}$sr$^{-1}$ would strongly suggest that UHE CR are produced by a top-down mechanism. On the contrary, if the photon flux in the region of the dip is smaller than $\sim 10^{-3}$ eV cm$^{-2}$s$^{-1}$sr$^{-1}$ and, at the same time, UHE CR have a large fraction of photons, the EGMF must be larger than $2 \times 10^{-12}$ G. The detailed calculation of the high energy photon spectrum in various models of UHE CR which takes into account synchrotron radiation in the Galactic magnetic field will be published elsewhere.

1. S.I. Nikolsky, I.N. Stamenov and S.Z. Ushev, J. Phys. G **G13** (1987) 883.
2. M. Aglietta *et al.*, Astropart. Phys. **6** (1996) 71;
3. M.C. Chantel *et al.*, Phys. Rev. Lett.**79** (1997) 1805;
4. R.J. Could, G. Schreder, Phys. Rev. Lett. **16** (1966) 252;
   J.P. Jelley, Phys. Rev. Lett. **16** (1966) 479.
5. P. Blasi, *Gamma Rays from Superheavy Relic Particles in the Halo*, astro-ph/9901390;
6. S.L. Dubovsky, P.G. Tinyakov, astro-ph/9906092.
7. S. Lee, Phys. Rev. **D58** (1998) 043004;
8. T. Stanev, Astrophys. J., **479** (1997) 290.